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# **Use of Waste for Heat, Electricity and Transport – Challenges when performing Energy System Analysis**

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## **ABSTRACT**

This paper presents a comparative energy system analysis of different technologies utilizing organic waste for heat, power and fuel for transport production. Technologies included in the analysis are 2<sup>nd</sup> generation biofuel production, gasification, fermentation (biogas production) and improved incineration. It is argued that it is important to assess energy technologies together with the energy systems of which they form part and influence. The energy system analysis is performed using the EnergyPLAN model, which simulates the Danish energy system hour by hour. The analysis shows that most fuel is saved by gasifying the organic waste and using the syngas for combined heat and power production. On the other hand least greenhouse gases are emitted if biogas is produced from organic waste and used for combined heat and power production. The technology which provides the cheapest CO<sub>2</sub> reduction is gasification of waste with subsequent conversion of the gas into transport fuel.

## **INTRODUCTION**

In Denmark 27% of the waste produced in 2004 was incinerated for heat and power production. Of the remaining amounts, 64% was recycled and only 8% land filled [1]. In the EU, municipal waste is, at present, disposed of through landfilling (49%), incineration (18%), and recycling and composting (33%) [2]. The EU has, however, introduced aims which significantly reduce the amounts of biodegradable waste, which may be landfilled. According to these aims, the amount of biodegradable waste deposited at landfills must not in 2014 exceed 35% of the amount of biodegradable waste produced in 1995 [3]. Consequently, at the EU level, great efforts are made to identify alternatives to landfilling of biodegradable waste.

In Denmark, 34 Danish waste incineration plants contribute with 4% of the Danish electricity production and 18% of the heat production. 75% of the waste resource incinerated is biodegradable waste. 70 Danish biogas plants contribute with a mere 1% of the electricity production and 1% of the heat production. [4]

In January 2007, the Danish Government presented its vision for the Danish energy sector towards 2025. According to the vision, the aim is to reach a level of 30% of energy consumption supplied by means of renewable energy in 2025, compared to 14% today, and to have a share of 10% of biofuel in the transport sector in 2020 [5]. Comparisons with similar European aims show an increase in the level of renewable energy in the EU as a whole from less than 7% today to 20% by 2020 and a minimum of 10% biofuels [6]. The utilisation of waste for energy can contribute to these goals.

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Furthermore, several trends make it interesting to use the waste resources in a different manner:

- Waste amounts are increasing all over Europe. Recent analyses project the amount of waste generated in Denmark to increase in the future. In these analyses, incinerable waste is expected to rise by 30% up to year 2020 and food and wood waste each by 40%. [1]
- The Danish waste incineration capacity is becoming too low for the growing amounts.
- The energy system needs flexibility to integrate more wind.
- The demand for transport continues to increase [7]. As the sector currently runs on fossil fuels, CO<sub>2</sub> emissions from the sector continue to increase. This may be decreased by producing transport fuels from waste.
- A new building code makes it mandatory to reduce the energy consumption in houses, which may result in an overall decrease in the demand for heat [8]. Already, waste incineration plants have insufficient heat markets and periodically need to cool off heat.

New technologies make it possible to utilize organic waste in a new way to achieve higher power efficiency, to store energy or to produce fuels for transportation. Interesting technologies include 2nd generation biofuel production, gasification/pyrolysis, anaerobic digestion and improved incineration. In a system perspective, the new technologies have potential benefits, such as the possibilities of regulating the production of electricity, heat and transport fuels and thereby increase the flexibility of the system. It is therefore important to perform Energy System Analysis as opposed to analyzing the technologies at individual level.

A number of Life Cycle Assessment (LCA) and Well-To-Wheel studies have been performed which illustrate the environmental effects - particularly the greenhouse gas emissions - of different technologies utilizing renewable energy including biomass for transportation purposes such as [9;10]. Likewise LCA studies have been performed on uses of waste for energy e.g. [11-13]. These studies compare strings of technologies from e.g. production of biofuels, upgrading, distribution to utilization of the fuels in vehicles. However, the studies do not analyze the technologies and their advantages and disadvantages seen from an energy system perspective or their influence on the energy system in which they exist.

Furthermore, it is important to ensure that the characteristics of the new technologies are represented in the Energy System Analysis model, so that potential benefits, such as flexibility and multiple outputs are illustrated, and restrictions, for instance on storage, are taken care of.

Below, some of the main differences between traditional fossil-fuelled combined heat and power (CHP) plants and the new technologies are illustrated.

Table 1. Differences between traditional fossil fueled CHP plants and new technologies

	Fossil fuel CHP	New waste technologies
Products	Electricity and heat	Multiple products such as heat, electricity, gaseous or liquid fuels, waste treatment and by-products (e.g. fodder and fertilizer)
Fuel	Single fuel plants (typically coal or gas)	Multiple fuels possible (e.g. waste, coal, biomass, manure, straw etc.)
Storage	Storage possible for infinite time	Not allowed to store household waste and wet biomass rapidly degrades
Geographical distribution	Fuel can be stored and transported easily	Location of fuel is important as fuel is not easily stored and has low energy content per volume
Fuel prices	Determined by world market prices	Waste price determined by national taxes

In this Energy System Analysis of the Danish energy system, it is attempted to take these characteristics into account. Through the analysis, it is assessed how the utilization of 10 TWh waste for incineration, fermentation or gasification producing electricity, heat and transport fuel may contribute to reducing the dependency of fossil fuels and to reducing greenhouse gas emissions in the most cost-effective way.

In the Methodology chapter use of the Energy System Analysis model is explained and the scenarios are presented. In the Results chapter the results are illustrated and recommendations are made for the future use of organic waste in the Danish energy system. Subsequently in the Sensitivity Analysis chapter sensitivity analyses of different parameters is presented. Finally in the Conclusions and Discussion chapter conclusions are drawn with respect to the use of the model for the purpose of evaluating the different technologies and suggestions are made for future analysis.

## METHODOLOGY

In the following sections, first the model which was used for the analysis is described and, subsequently, the technical alternatives are analysed.

The Energy System Analysis was made using the EnergyPLAN model, which is developed at Aalborg University and available for free together with documentation online [14]. A brief description of the model is presented in Appendix A. For more thorough explanations consult [14;15].

The following input must be given to the model:

- The energy content of the waste resource divided into the three types of district heating systems mentioned above. Other resources can be included, but the cost and the CO<sub>2</sub> content of the waste will then have to be adjusted accordingly.
- Efficiencies specifying the energy output in the following 4 energy forms: Heat for district heating, electricity, fuel for transportation and fuel for CHP and boilers. Moreover, one can specify an additional non-energy output (such as animal food), which will then be given an economic value in the feasibility study. In this way, the multiple products are taken into account.
- An hour by hour distribution of the waste input (and hence heat and electricity output).

Basically, the model assumes that waste cannot be stored but has to be converted in accordance with the specified hour by hour input.

The model is a simplified model in which the energy system is divided into three groups:

1. District Heating Plants
2. Decentralised CHP Plants
3. Centralised CHP Plants

Each group represents areas supplied with the mentioned technologies. The geographical distribution is hence not included in the analysis and this aspect would have to be dealt with by a supplementary analysis e.g. using Geographical Information Systems.

### Technical alternatives

Eight different scenarios illustrating different ways of utilizing waste for energy production are modelled. The scenarios focus on incineration, biogas and gasification technologies:

- **NoWaste.** Waste is not used for energy but either landfilled or composted
- **WasteHeat.** Waste is used only for heat in new plants with efficiencies of 2004
- **WasteCHP (today).** Waste is incinerated in today's plants, where 96% are CHP plants and just 4% produce only heat [16].
- **WasteCHP (new).** Waste is incinerated in new plants with efficiencies of 2004
- **BiogasCHP.** An organic fraction of 1 TWh is used for producing biogas, which is used for CHP production. 0.6 TWh manure is added to the organic fraction with a distribution of 80% manure to 20% organic waste. The biogas is produced in large-scale centralised biogas plants with a capacity of 800t/d. When fermented the biomass is separated and the fibre fraction is burned in a waste incineration plant.
- **BiogasTransport.** Again the organic fraction produces biogas, but the biogas is upgraded to natural gas quality and used in natural gas vehicles. Manure is added as above
- **SyngasCHP.** The Syngas scenarios use the planned REnescience process as case [17]. For this analysis the process is split into a CHP and a transport scenario. The REnescience project however plans to produce both CHP and transport fuel. In the SyngasCHP scenario 1 TWh organic fraction is gasified and used for CHP production. The waste is first liquefied by non-pressurised heat treatment and subsequently gasified in an entrained flow gasifier with 25% organic waste and 75% coal. The syngas is then used in a single cycle gas turbine.
- **SyngasTransport.** Again the waste is gasified and then converted into petrol and used in petrol vehicles

The total amount of waste considered equals 10 TWh, which was the amount of waste used for energy purposes in Denmark in 2004. For the biogas and the syngas scenarios, 1 TWh organic waste is used in the respective plants. This amount is comparable to the total amount of organic waste from households [12]. The remaining waste fraction of 9 TWh is incinerated in new plants with efficiencies of 2004. Furthermore, 0.6 TWh manure is facilitated in the biogas scenarios and 3 TWh coal is induced in the syngas scenarios.

The efficiencies of the plants are illustrated in Appendix B. The electric efficiency increases from 14.4% of today's average to an average efficiency of 19.5% of new plants. Biogas plants have a lower efficiency than gasification plants, but have the advantage of facilitating the use of manure in the energy system.

The CO<sub>2</sub> content of the waste related to fossil parts is assumed to be 24 kg/GJ [18]. In Appendix B the Lower Heating Values and biogas yields are illustrated.

### Reference Energy System

The reference energy system, in which the technologies are used, is the Danish energy system in 2004. Compared to other countries, the Danish energy system has a high total energy efficiency with a high level of CHP (55% of the thermal electricity production and 82% of district heating) and a high percentage of wind (18.5% of total electricity production) [7]. For all scenarios, the same amount of electricity, heat and transport fuel is supplied at the same hours throughout the year.

The system is analyzed with no transmission to neighbouring countries and a technical optimization is chosen, where the model seeks to find solutions with the lowest fuel consumption. In order to ensure this, CHP plants operate according to both the heat and the electricity demands.

## RESULTS

In this chapter, differences in fuel substitution and CO<sub>2</sub> emissions as well as in costs are illustrated when utilizing the waste in different ways.

### Fuel consumption

The figure below illustrates the fossil fuel substituted with waste in the various scenarios.

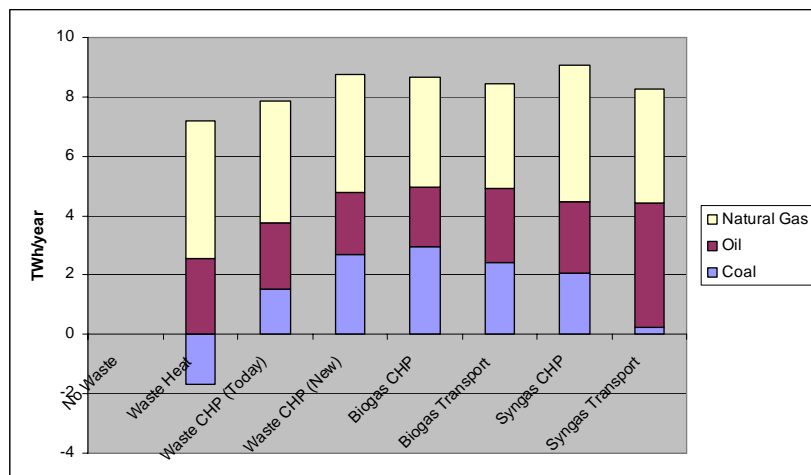


Figure 1. Fossil fuel substituted when utilizing 10 TWh waste per year. Including 2.5 Mt manure for biogas and 3 TWh coal for syngas

In the WasteHeat scenario a consumption of coal is induced for electricity production. If more wind turbine capacity was installed in the future and it was possible to produce the needed electricity with wind power instead the large coal consumption would not be induced. The remaining scenarios do not induce fossil fuel consumptions, but rather substitutes around 8-9 TWh fossil fuel each.

The scenario that reduces the fossil fuel consumption by the largest percentage is the SyngasCHP scenario, followed by the new WasteCHP scenario and the biogas scenarios. The

SyngasTransport scenario substitutes most oil, whereas the WasteHeat scenario substitutes most natural gas and the BiogasCHP scenario substitutes the largest amount of coal.

## CO<sub>2</sub> emissions

Utilizing waste in the energy system results in reduced CO<sub>2</sub> emissions from energy conversion in the Danish energy system, as illustrated in the figure below.

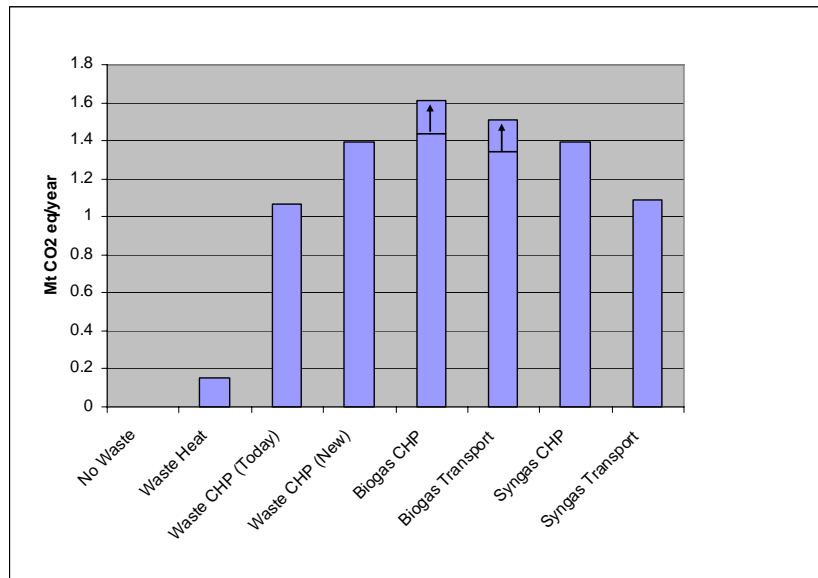


Figure 2. Reduced CO<sub>2</sub> emissions from energy conversion in the various scenarios and arrows indicating reduced CH<sub>4</sub> and N<sub>2</sub>O emissions due to digestion of manure

The worst solution would be not to utilize waste for energy purposes. Utilizing waste only for heat results in negligible CO<sub>2</sub> emissions. It may furthermore be seen that today's use of waste for energy saves the Danish society of approximately 1 Mt CO<sub>2</sub> eq every year. The highest reduction in CO<sub>2</sub> emissions is achieved by utilizing organic waste in biogas plants for CHP closely followed by the new WasteCHP, SyngasCHP and BiogasTransportation scenarios.

If seen in a lifecycle perspective, the main differences in emissions of greenhouse gases between the scenarios, which are not already accounted for, are based on the fact that more methane will be emitted in the NoWaste scenario and less methane and N<sub>2</sub>O will be emitted in the biogas scenarios. If waste is e.g. landfilled in the NoWaste scenario, methane emissions from landfill sites should be added to the emissions and not using waste for energy would produce an even more negative result.

The reduced methane and N<sub>2</sub>O emissions in the biogas scenarios are the results of digested manure used in the fields as opposed to raw manure. An increase in transport is expected but an emission from this is heavily outweighed by the reduced methane and N<sub>2</sub>O emissions [19]. If the biogas scenarios are credited for further net reduced greenhouse gas emissions, the biogas columns can be increased to the level indicated by the arrows [9]. This results in the BiogasCHP scenario coming out even better and the second best solution being the BiogasTransport scenario.

## Economic Analysis

In this section, the costs of the energy system with the different scenarios are presented. In the table below, the costs used for the analysis are illustrated. The WasteCHP (today) scenario is not included in the analysis, since the costs and the rate of depreciation of the existing plants are not known. Fuel prices corresponding to an oil price of 36 USD/bbl is used, as this corresponds to the cost in Denmark in 2004. For waste, a fuel price of minus 20 DKK/GJ<sup>1</sup> is used.

Table 2. Investment and Operation and Maintenance Costs as well as normal plant capacities, availability and lifetimes.

Reference technologies	Capacity	Investment	O&M	Availability	Life-time	Year	Source
	PJ/a	MEUR/PJ	%	%	Years		
WasteHeat	1.3	33.5	9	98	20	2004	[21]
WasteCHP (new)	1.3	52.2	7	98	20	2004	[21]
BiogasCHP	3.0	355.6	7	98	20	2004	[21]
BiogasTransport	3.0	573.2	7	98	20	2004	[21]
SyngasCHP	27.5	44.0	5	80	20	2010-20	[9]
SyngasTransport	9.6	33.1	5	85	20	2010-20	[9]
Technical alternatives							
BiogasTransport Low	3.0	480.6	7	98	20	2004	
Syngas High	4.6	120.8	4	80	20	2010	[22]
Coal PP	3.0	148.2	3	91	30	2004	[21]

Data for the syngas scenarios are taken from a European Well-To-Wheel study [9]. As exact data for similar plants are not available in the study, it is attempted to use data from plants with similar technologies and capacities. For SyngasCHP, data for a Coal-based Integrated Gasification Combined Cycle (IGCC) plant are used. For SyngasTransport, data for a Black Liquor-based gasification plant producing synthetic diesel are used. For the Syngas High scenarios data for an IGCC plant are taken from a report from the United States' Environmental Protection Agency [22]. It is assumed that costs for the combined cycle are comparable to those of the catalyst converting syngas to petrol.

For the BiogasTransport scenario the additional cost of natural gas cars compared to conventional cars is included. A natural gas car is assumed to cost 25% more than a conventional car [23]. In the BiogasTransport Low scenario it is assumed to cost only 10% extra. Alternative investment costs are only analysed for the BiogasTransport and syngas scenarios as these are the newest technologies and data for these technologies are most uncertain.

In the NoWaste and WasteHeat scenarios, no power is produced. It may, therefore, be necessary to invest in additional power capacity such as a coal-fired power plant. Data from a

<sup>1</sup> In Denmark the cost of incinerating waste in 2004 was around 633DKK/t and the income from energy services was 419 DKK/t leaving 214 kr/t equivalent to 20 DKK/GJ to be paid by the municipalities for the waste treatment service [20]. The income from energy services is regulated by a maximum price on the heat delivered.



coal-fired steam turbine with advanced steam process is used for exemplifying the additional costs [21].

The figure below illustrates the increased total annual costs of the energy system when using the waste for energy. It should, however, be noted, that alternative costs of treating the waste will occur elsewhere in society if the waste is not used for energy production. These costs are not included in the present analysis. CO<sub>2</sub> quota costs are not included in the analysis, either.

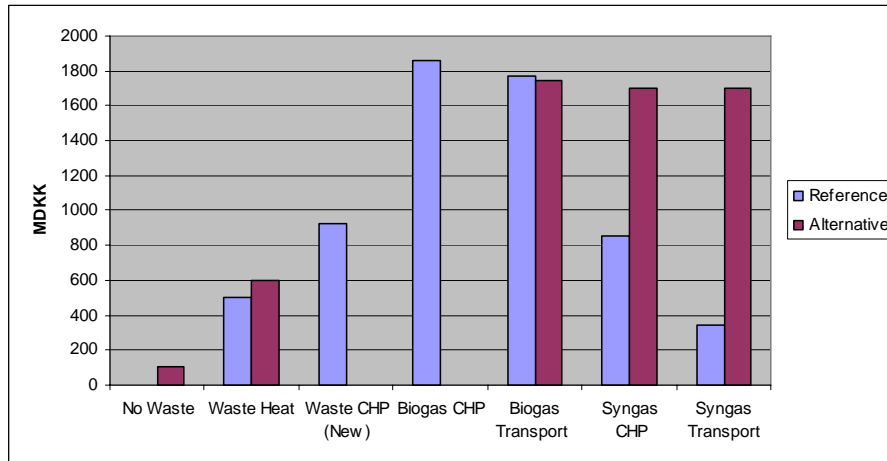


Figure 3. Difference in annual costs between the NoWaste and the other scenarios

As can be seen, the use of waste results in increased annual costs for all scenarios compared to not using waste for energy, even when investments in additional power plants are included, as seen in the right bars with the NoWaste and WasteHeat scenarios. Alternative costs of handling the waste are however not included.

The largest difference between the reference and the alternative technology is seen in the SyngasTransport scenario where the annual costs compared to the NoWaste scenario are five times as high as in the reference. The large differences in the syngas scenarios illustrate the uncertainty in investment costs.

The increased annual costs should be compared to the CO<sub>2</sub> reduction potential, as in the figure below.

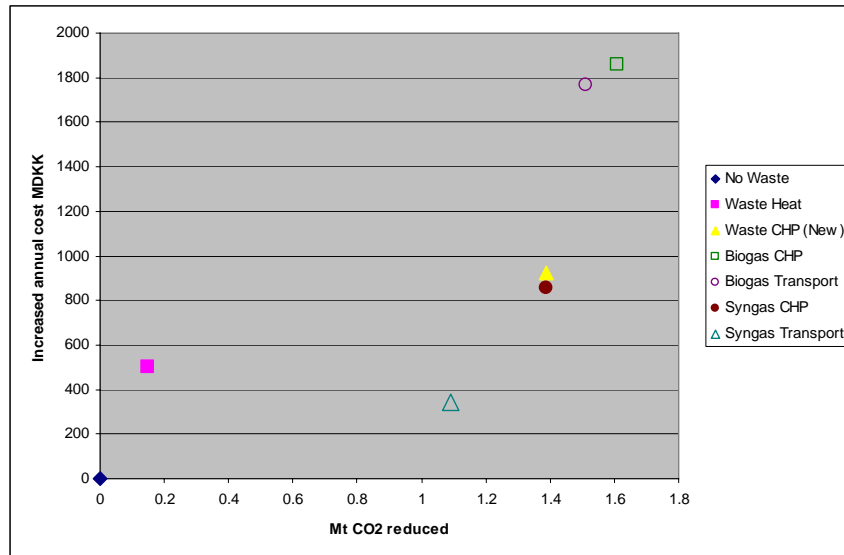


Figure 4. Increased annual cost versus CO<sub>2</sub> reduction potential. For biogas including reduced CH<sub>4</sub> and N<sub>2</sub>O emissions due to digestion of manure

The biogas scenarios are the most expensive solutions in absolute terms, but since they also have high CO<sub>2</sub> reduction potentials, they do not have the highest CO<sub>2</sub> reduction costs. WasteHeat has the highest CO<sub>2</sub> reduction costs, since it has a very low CO<sub>2</sub> reduction potential. The SyngasTransport scenario has the lowest CO<sub>2</sub> reduction costs, if the cost data of the reference prove to hold.

It should be noted that an actual CO<sub>2</sub> reduction cost cannot be calculated on the basis of these data. Today's system should be used as a baseline instead of the NoWaste scenario; alternative costs of handling the waste in the NoWaste scenario should be included, and CO<sub>2</sub> equivalents should be calculated for the full lifecycle of all scenarios. Notably, including the methane emissions from landfilling or from composting would make a difference in favour of using waste for energy, but would not change the ranking of the scenarios.

## SENSITIVITY ANALYSIS

Results of the sensitivity analysis are presented in Appendix C. Sensitivity analyses are performed for the fuel price, the organic waste handling costs, the interest rate and the fossil CO<sub>2</sub> content of waste:

- For the reference an oil price of 36 USD/bbl is used. With a high oil price of 68 USD/bbl all scenarios come out better and the SyngasTransport scenario even results in a reduction in annual costs.
- Even with low organic waste handling costs the CO<sub>2</sub> reduction cost of the biogas scenarios remains higher than the reduction costs for WasteCHP and the syngas scenarios.
- Changing the interest rate or the fossil CO<sub>2</sub> content of waste does not change the ranking of the scenarios, but using the high content of fossil CO<sub>2</sub> converts the minor CO<sub>2</sub> reductions of 0.15 Mt obtained in the WasteHeat scenario into an increase in CO<sub>2</sub> emissions of 0.17 Mt.

## CONCLUSION AND DISCUSSION

The results of the Energy System Analysis are useful in two respects:

1. They support decision-making directly, when the focus is on dependence of fossil fuels
2. They supply input regarding both CO<sub>2</sub> emissions from conversion in the energy system and fuel consumption to further environmental assessment e.g. using Life Cycle Assessment (LCA) methodology

The clearest conclusion of the analysis is that waste should be used for energy purposes and not incinerated to produce only heat. Furthermore, if the main political aim is to reduce the dependence on fossil fuels the best solution is to produce syngas for CHP closely followed by upgrading the CHP incineration plants. The worst solution is to use the waste for heat production. The reduction of oil dependence is best achieved by using syngas for transport.

If, on the other hand, the main political aim is to reduce greenhouse gas emissions, then the best solution is to utilize the organic waste for biogas production and, subsequently, to use the biogas for CHP production. The worst solutions would be to incinerate the waste for heat production or not to utilize the waste for energy production, at all. This conclusion should, however, be substantiated by performing LCAs for the remaining life cycles of the scenarios.

The cheapest reduction of CO<sub>2</sub> in the energy system is obtained with the SyngasTransport scenario when compared to the NoWaste scenario. Traditionally, the utilization of waste for CHP production has been regarded as the most efficient technology, but the SyngasTransport solution seems promising both in terms of costs, CO<sub>2</sub> reduction potential and potential of using waste for transportation. This conclusion does, however, depend heavily on whether it will be possible to achieve the low investment costs used.

It would be interesting to perform further Energy System Analyses with open borders facilitating trade with electricity and to assess the economy of the various scenarios. Furthermore, it would be interesting to assess the performance of the technologies in possible future energy systems with more wind power. Finally, to give full credit to the flexibility of the systems choosing between producing electricity and heat or transport fuels it would be interesting to develop the model further to reflect these features.

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## REFERENCES

- [1] F. Møller Andersen and H. V. Larsen, "A Model for Projection of Isag Data – FRIDA," Roskilde: Risø National Laboratory, 2006.
- [2] European Commission, "Taking sustainable use of resources forward: A Thematic Strategy on the prevention and recycling of waste," Brussels: 2005.
- [3] Council Of The European Union, "Council Directive 1999/31/EC of 26 April 1999 on the landfill of waste," 1999, pp. 0001-0019.
- [4] Danish Energy Authority, "Energy Statistics 2004," Copenhagen: Danish Ministry of Transport and Energy, 2005.
- [5] Danish Government, "A Visionary Danish Energy Policy," Copenhagen: 2007.
- [6] European Commission, "An Energy Policy For Europe," Brussels: 2007.
- [7] Danish Energy Authority, "Energy Statistics 2004 (In Danish)," Copenhagen: 2005.
- [8] Danish Government, "Law about increasing energy savings in buildings (in Danish), LOV no 585 of 24/06/2005," Copenhagen: 2005.
- [9] EUCAR, CONCAWE, and Joint Research Centre of the EU Commission, "Well-To-Wheels Analysis Of Future Automotive Fuels And Powertrains In The European Context - WELL-to-WHEELS Report Version 2c," Joint Research Centre of the EU Commission, 2007.
- [10] C. N. Hamelinck and A. P. C. Faaij, "Outlook for advanced biofuels," *Energy Policy*, vol. 34, no. 17, pp. 3268-3283, 2006.
- [11] G. Finnveden, "Methodological aspects of life cycle assessment of integrated solid waste management systems," *Resources, Conservation and Recycling*, vol. 26, no. 3-4, pp. 173-187, June 1999.
- [12] A. Baky and O. Eriksson, "Systems Analysis of Organic Waste Management in Denmark," in *Environmental Project no. 822, 2003* Copenhagen: Danish Environmental Agency, 2003.
- [13] J. T. Kirkeby, H. Birgisdottir, T. L. Hansen, T. H. Christensen, G. S. Bhandar, and M. Hauschild, "Evaluation of environmental impacts from municipal solid waste management in the municipality of Aarhus, Denmark (EASEWASTE)," *Waste Management & Research*, vol. 24, no. 1, pp. 16-26, 2006.
- [14] H. Lund, "EnergyPLAN, Advanced Energy System Analysis Computer Model version, Documentation version 7.0.," Aalborg: Aalborg University, 2007.
- [15] H. Lund and E. Munster, "Modelling of energy systems with a high percentage of CHP and wind power," *Renewable Energy*, vol. 28, no. 14, pp. 2179-2193, 2003.
- [16] ISWA, "Energy from Waste State-of-the-Art-Report ,", 5th Edition August 2006 ed Copenhagen: ISWA Working Group on Thermal Treatment of Waste, 2006.
- [17] DONG Energy, "Personal Communication regarding RENescience," Skærbæk: 2007.
- [18] C. Petersen and I. Domela, "Composition of municipal waste and schemes for homecomposting (In Danish)," Miljøprojekt 868 ed Danish Environmental Protection Agency, 2003.
- [19] L. H. Nielsen, K. Hjort-Gregersen, P. Thygesen, and J. Christensen, "Socio-economic Analysis of Centralised Biogas Plants - with technical and corporate economic analysis (In Danish)," Report no. 136 ed Copenhagen: Institute of Food and Resource Economics, 2002.
- [20] RenoSam, "Still more efficient waste treatment - Benchmarking 2006 (In Danish)," 2006.
- [21] Danish Energy Authority, ElkraftSystem, and Eltra, "Technology Data for Electricity and Heat Generating Plants," Copenhagen: Danish Energy Authority, 2005.
- [22] I. Nexant, "Final Report Environmental Footprints and Costs of Coal-Based Integrated Gasification Combined Cycle and Pulverized Coal Technologies ,", EPA-430/R-06/006 ed U.S. Environmental Protection Agency Office of Air and Radiation, 2006.
- [23] K. Jørgensen, "Natural gas car costs - Personal communication," 2007.

- [24] M. Persson, "Assessment of upgrading techniques for biogas (In Swedish)," in *Rapport SGC 142* Svenskt Gastekniskt Center, 2003.
- [25] Danish Environmental Protection Agency, "Status on organic municipal waste (in Danish)," in *Orientation from the Environmental Protection Agency No. 4 2003* Copenhagen: 2003.
- [26] H. B. Moller, S. G. Sommer, and B. Ahring, "Methane productivity of manure, straw and solid fractions of manure," *Biomass & Bioenergy*, vol. 26, no. 5, pp. 485-495, 2004.
- [27] K. Hjort-Gregersen and J. Christensen, "Burning of fibre fraction from separated manure - Corporate and socio-economic analyses (In Danish)," Copenhagen: Institute for Food and Economy, 2005.
- [28] C. Damsgaard and L. Strandmark, "Should the foodwaste of households be burned or recycled? (In Danish)," in *Socioeconomic analysis of increased recycling of organic municipal waste* Danish Environmental Protection Agency, 2003.
- [29] Danish Energy Authority, "Guidelines in socioeconomic analysis in the field of energy," in *Appendix: Assumptions for socioeconomic analysis in the field of energy* Copenhagen: Danish Energy Authority, 2007.
- [30] J. B. Illerup and et.al., "Denmark's National Inventory Report 2006 - Submitted under the United Nations Framework Convention on Climate Change, 1990-2004," in *NERI Technical Report No. 589* National Environmental Research Institute, Ministry of the Environment, 2006.
- [31] Danish Environmental Protection Agency, "Waste 21," in *The Government's Waste Plan 1998-2004* Danish Environmental Protection Agency, 1999.
- [32] Waste Centre Denmark, "Fossil CO<sub>2</sub> content in waste - Personal communication," 2007.

## APPENDIX A - THE ENERGYPLAN MODEL

The EnergyPLAN model is a deterministic input/output simulation model. Inputs to the model may be divided into five sets of data:

- Demands for electricity, heat, cooling, industry, individual households and transport
- Renewable Energy Supply
- Capacities and efficiencies of a.o. CHP and power plants
- Technical limitations and definition of external power market
- Fuel costs and CO<sub>2</sub> emission factors

The fluctuating demands, production and prices are fed in as hourly distributions over a year. The input data are regulated by a number of strategies illustrating e.g. how CHP plants are operated on the market and how critical excess electricity production is reduced. Results are, among others, heat and power production, import/export of electricity, forced excess electricity production, fuel consumption, CO<sub>2</sub> emissions and share of renewable energy in the system.

The model is a simplified model in which the energy system is divided into three groups:

4. District Heating Plants
5. Decentralised CHP Plants
6. Centralised CHP Plants

Each group represents areas supplied by the mentioned technologies. The geographical distribution is hence not included in the analysis and this aspect would have to be dealt with by a supplementary analysis, e.g. using Geographical Information Systems.

The model can both simulate a closed system with no electricity exchange and an open system. It is interesting to evaluate whether the energy system can utilize the energy produced at a given hour in order to ensure an efficient system, which in turn can facilitate the trade of electricity at times when the Danish actors want it and not when they are forced to do so. Likewise, the model can perform either a technical optimization focusing on improving the fuel efficiency of the system or a market optimization focusing on improving the financial output of the individual plant owners.

Previously, waste has been treated in the model as a fuel along with biomass resources. However, as a part of this study, the utilization of waste in the EnergyPLAN computer model has been made more detailed and is now conducted in the way described below.

The following input must be given to the model:

- The energy content of the waste resource divided into the three types of district heating systems mentioned above. Other resources can be included, but the cost and the CO<sub>2</sub> content of the waste will then have to be adjusted accordingly.
- Efficiencies specifying the energy output in the following 4 energy forms: Heat for district heating, electricity, fuel for transportation and fuel for CHP and boilers. Moreover, one can specify an additional non-energy output (such as animal food), which will then be given an economic value in the feasibility study. In this way, the multiple products are taken into account.
- An hour by hour distribution of the waste input (and hence heat and electricity output).

Basically, the model assumes that waste cannot be stored but has to be converted in accordance with the specified hour by hour input. Consequently, the energy outputs are treated in the following way:

Heat production for district heating is given priority along with solar thermal and industrial waste heat production. If such input cannot be utilized because of limitations in demand and heat storage capacity, the heat is simply lost. Electricity production is fed into the grid and given priority along with renewable energy resources such as wind power. Other units, such as CHP and power plants, will adjust their production accordingly if possible (given the specified regulation strategy), and if this cannot be done, excess electricity production will be exported.

The amount of transport fuel produced is calculated and the user can subtract it from the total use of the relevant fuel in the reference and, at the same time, adjust for differences in car efficiencies, if such differences exist. Fuel for CHP and boilers is automatically subtracted in the calculation of fuel in the relevant district heating groups.

## APPENDIX B – EFFICIENCIES AND ENERGY CONTENT

Table 3. Efficiencies and waste amounts used for the scenarios.\*Including 0.6 TWh manure

Technical alternatives	Waste incineration				Biogas or gasification				Source
	Mixed waste	Elec- tric eff.	Heat eff.	Heat only eff.	Org. waste	Elect ric eff.	Ther mal eff.	Fuel eff.	
	TWh	%	%	%	TWh	%	%	%	
NoWaste	0				0				[21]
WasteHeat	10			85.5	0				[21]
WasteCHP (today)	10	14.4	70.9	75.0	0				[16]
WasteCHP (new)	10	19.5	65.4	85.5	0				[21]
BiogasCHP	9	19.5	65.4	85.5	1.6*	18.6	17.5		[21]
BiogasTransport	9	19.5	65.4	85.5	1.6*			38.6	[24]
SyngasCHP	9	19.5	65.4	85.5	1	36.6	35.0		[17]
SyngasTransport	9	19.5	65.4	85.5	1	11.0	10.5	54.4	[17]

Table 4. Lower heating values and biogas output. \*Based on LHV of dry matter content in the manure

Fuel	LHV	Biogas output
Mixed waste	10.5 MJ/kg [7]	
Organic waste	5.7 MJ/kg [25]	108 Nm3/t [25]
Manure	0.9 MJ/kg* [26]	21 Nm3/t [21]
Fibre fraction from biogas plant	3.8 MJ/kg [27]	
Biogas	23 MJ/m3 [21]	



## APPENDIX C - SENSITIVITY ANALYSIS

Sensitivity analyses are performed for the fuel price, the organic waste handling cost, the interest rate and the fossil CO<sub>2</sub> content of waste.

### Fuel price

In the reference scenarios, fuel prices corresponding to an oil price of 36 USD/bbl is used, as this corresponds to the cost in Denmark in 2004. Fuel prices have, however, gone up since then and, consequently, an alternative corresponding to an oil price of 68 USD/bbl is used. 68 USD/bbl was the average price in Denmark in 2006.

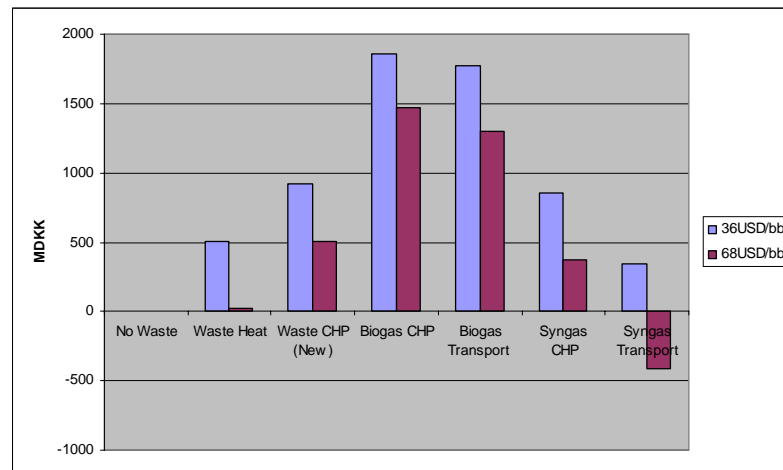


Figure 5. Difference in annual costs between the NoWaste and the other scenarios with 36 USD/bbl and 68 USD/bbl

The SyngasTransport scenario results in a reduction in annual costs when the oil price rises to 68 USD/bbl, as can be seen from the figure above. With the increased fuel price, the WasteHeat scenario also achieves reduction costs below 150 DKK/t CO<sub>2</sub> without investment in alternative power plants.

### Handling cost organic household waste

A report from the Danish Environmental Agency from 2003 analyses Danish pilot projects in the field of sorting organic household waste for anaerobic digestion and composting. A broad spectrum of handling and transportation costs were identified in the analysis, from 1754-3415 DKK/t organic waste in single-family houses and from 1640-1830 DKK/t organic waste in multi-story houses [28]. For the reference scenario, an average of each category is used. For the sensitivity analysis, the lowest prices are combined to form low-cost biogas scenarios and likewise with the high costs.

With the high costs, the biogas scenarios get even higher annual costs and although the low-cost scenario reduces the costs considerably, the CO<sub>2</sub> reduction costs of the biogas scenarios remain higher than the reduction costs of WasteCHP and the syngas scenarios.

### Interest rate

In the reference scenarios, an interest rate of 3% is used. If the interest rate is increased to 6%, the SyngasCHP, WasteCHP (New) and SyngasTransport are most affected since the investment

constitutes a relatively larger share of the total annual cost. The ranking of the scenarios, however, does not change.

## **CO<sub>2</sub>**

The Danish Energy Authority recommends using a CO<sub>2</sub> content of 18 kg/GJ originating from the fossil part of the waste [29]. This is equivalent to a plastic content of 6.6% [30]. The figure originally came from the Danish Government's Waste Plan 1998-2004 [31]. A more recent Danish analysis, however, shows a plastic content of minimum 9.1% [18]. If this figure is used, a fossil CO<sub>2</sub> content of 24 kg/GJ is found, which is the figure used for the reference. Furthermore, Waste Centre Denmark calculates with a figure of 33 kg/GJ [32].

Varying the contents of CO<sub>2</sub> in the waste does not change the ranking of the scenarios as the same amount of waste is used in each scenario. However, 0.23 Mt CO<sub>2</sub> less than in the reference is emitted when calculating with 18 kg/GJ and 0.32 Mt more CO<sub>2</sub> is emitted when using 33 kg/GJ. Consequently, if the high content is used, the minor CO<sub>2</sub> reductions of 0.15 Mt obtained in the WasteHeat scenario is converted into an increase in CO<sub>2</sub> emissions of 0.17 Mt.